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SATELLITE OCEAN COLOR: PRESENT STATUS, FUTURE CHALLENGES

Watson W. Gregg
and
Charles R. McClain
NASA/Goddard Space Flight Center
Laboratory for Hydrospheric Processes
Greenbelt, MD 20771

We are midway into our 5th consecutive year of nearly continuous, high quality ocean color observations from space. The Ocean Color and Temperature Scanner/Polarization and Directionality of the Earth's Reflectances (OCTS/POLDER: Nov. 1996-Jun. 1997), the Sea-viewing Wide Field-of-view Sensor (SeaWiFS: Sep. 1997-present), and now the Moderate Resolution Imaging Spectrometer (MODIS: Sep. 2000-present) have and are providing unprecedented views of chlorophyll dynamics on global scales. Global synoptic views of ocean chlorophyll were once a fantasy for ocean color scientists. It took nearly the entire 8-year lifetime of limited Coastal Zone Color Scanner (CZCS) observations to compile seasonal climatologies. Now SeaWiFS produces comparably complete fields in about 8 days. For the first time, scientists may observe spatial and temporal variability never before seen in a synoptic context. Even more exciting, we are beginning to plausibly ask questions of interannual variability. We stand at the beginning of long-time time series of ocean color, from which we may begin to ask questions of interdecadal variability and climate change. These are the scientific questions being addressed by users of the 18-year Advanced Very High Resolution Radiometer time series with respect to terrestrial processes and ocean temperatures. The nearly 5-year time series of ocean color observations now being constructed, with possibilities of continued observations, can put us at comparable standing with our terrestrial and physical oceanographic colleagues, and enable us to understand how ocean biological processes contribute to, and are affected by global climate change.

The Past

Such progress did not occur easily. Lack of commitment and several launch delays led to a 10-year hiatus between global observations by the CZCS and OCTS/POLDER. These delays occurred despite the overwhelming success of the CZCS mission, and despite its severe limitations in coverage and operational duty cycle. It was a demonstration project, and consequently only operated upon request. During its 8-year lifetime (1978-1986), CZCS ocean coverage was so sparse that monthly and seasonal data composites contained vast unsampled oceanic areas, which differed in location from month-to-month and year-to-year.

These deficiencies limited our ability to observe interannual variability, but discoveries related to seasonal and spatial variability, the nature of phytoplankton distributions in the global oceans, and extrapolation to first-ever data-derived estimates of global ocean primary production more than demonstrated the importance of ocean color observations from space. An internet search identified nearly 1000 published papers related to the CZCS since its launch. These ranged from algorithm sensitivities and dependences, to the nature and causes of natural variability, to application of CZCS data in developing and validating biogeochemical models.

Lessons Learned

The purposes of a demonstration mission are two-fold: 1) to establish the technological and scientific feasibility, and 2) determine the improvements that must be made for a successful follow-on. The CZCS amply demonstrated the first objective. But nearly as important, it also clearly indicated deficiencies in its design and operations that were inadequate to meet the scientific objectives of a successor mission. In approximate order of priority, these deficiencies, or required improvements were

- 1) the need for routine, continuous global synoptic observations
- 2) better methods for characterizing aerosols
- 3) the need for a dedicated calibration and validation program over the lifetime of the mission including detailed pre-launch sensor characterization
- 4) methods to account for multiple scattering by aerosols and the interaction between scattering by molecules and aerosols
- 5) better signal-to noise ratios
- 6) the need to produce estimates of chlorophyll, not pigment
- 7) dedicated data systems for rapid processing and distribution
- 8) new information about chromophoric dissolved organic matter (CDOM)
- 9) the need to account for whitecap/foam reflectance

The Present

All of the modern global missions now flying, as well as proposed ones, meet the scientific requirements for ocean color observations. They are dedicated, routine observational platforms. They contain spectral bands in the near-infrared region of the spectrum to enable unequivocal determination of aerosol characteristics. Dedicated, high quality in situ calibration/validation activities were established before launch including detailed pre-launch analyses of sensor characteristics and behavior. Complex algorithms were designed and tested to account for aerosol multiple scattering and interactions with molecules. Signal-to-noise ratios were improved so that all the global missions have at least 500:1 for the visible wavelengths instead of 200:1 for the CZCS. All of the missions produce chlorophyll distributions as the primary output geophysical product. Data systems were designed and rigorously tested before launch, resulting in nearly immediately available derived geophysical products in the best case. A new spectral band was included at short wavelengths (near 410 nm) to help determine the distribution and abundance of CDOM. Finally, whitecap/foam reflectance algorithms were developed before launch and refined shortly afterward.

The Present

These modifications to the CZCS sensor design, operations, and algorithms have given rise to the unprecedented 4-½ year ocean color data set that we now have and can expect to continue for the near future. The scope, quality, and coverage of the data set has enabled us to investigate scientific problems and events that were before unattainable. Examples such as the monitoring of the 1997 El Niño and its effect on phytoplankton populations in the equatorial Pacific were captured by the OCTS and SeaWiFS records, along with the record intensity La Niña that followed until Sep. 2000. The intensity of the 1997 El Niño was so large, as recorded by SeaWiFS, that approximately 0.7 Pg of carbon dioxide did not enter the atmosphere that year. This represents about half the estimated

“missing carbon” in global carbon budgets. New estimates of CDOM distributions are being prepared using SeaWiFS data, along with improved estimates of primary production. SeaWiFS data were used to track a bloom resulting from the Southern Ocean Iron fertilization Experiment (still apparent 55 days after fertilization!). Ocean color data from this time series are indispensable in the development and validation of ocean biogeochemical models.

Continuous global observations of ocean color are the cornerstone of NASA’s contribution to ocean biogeochemical sciences. A long-term time series is crucial to enable us to observe and understand changes in the ocean biosphere ranging from short-term anomalies, interannual variability such as El Niño and La Niña, interdecadal oscillations, and long term climate change. It is the highest priority requirement for ocean carbon cycle research for NASA. The lack of an ocean color time series underscores the importance of ensuring that one can be established in the future. NASA is planning future missions containing ocean color sensors for the future, a second MODIS on the Earth Observing System Aqua platform due for launch in 2001, and two Visible and Infrared Sounders (VIIRS) in 2006, and in 2008.

The case has been amply made for continuity of satellite ocean color data. In fact, so much so that an explosion of international missions are flying or planned for the near future. These include the Global Imager (GLI) along with another POLDER, a Super-Global Imager (S-GLI), and the Medium Resolution Imaging Spectrometer (MERIS) for global observations and a fleet of more limited duty missions. The issue at hand is less continuity, which appears to be assured for the present, but how to manage and utilize ocean color data from multiple platforms. NASA scientists have estimated that significant improvements in short term coverage are possible with up to 3 satellites flying at the same time by avoiding sun glint, inter-orbit gaps, and some clouds, which can enable us to understand short-term events. These may be particularly important in the coastal oceans. But more than 3 provided diminishing returns. One of the major emphases of NASA’s Sensor Intercomparison for Marine Biological and Interdisciplinary Ocean Studies program is the problem of merging ocean color data from multiple satellites to improve our observational capability. The issue has progressed from continuity to complementarity, as emphasized by the International Ocean Color Coordinating Group.

The Future

There is great cause for optimism for the continued presence and improvement of global synoptic ocean color observations from space. But the future is never guaranteed, and the case for continued observations must be continually asserted.

However, the biggest challenges to the satellite ocean color community come to us externally. These are the challenges to improve our understanding of the global carbon cycle. These issues have importance extending well into climate change but also into the international policy arena. Recent negotiations into implementation policies for the international Kyoto treaty, which required reductions of fossil fuel emissions by most industrialized nations to pre-1990 standards, broke down over issues related to credits over carbon sinks. Nevertheless, climate models continue to predict 1.4-5.8 deg. C increases in global temperatures under an atmospheric CO₂ doubling scenario, according to the Third Assessment Report of the Intergovernmental Panel on Climate Change, which is now expected to occur at the end of the present century.

These issues present challenges to satellite ocean color because photosynthetic organisms, as seen in the surface layers by ocean color sensors, represent the source of virtually all organic carbon in the global oceans. Ocean color sensors, furthermore, produce the only remotely-sensed observation of biomass. Although phytoplankton biomass represents only a small fraction of Earth carbon budget, they represent about 50% of the carbon fixation through photosynthesis. Virtually all large-scale models of ocean primary production utilize satellite-derived estimates of chlorophyll. Spaceborne observations of chlorophyll often factor non-linearly in these models. For these reasons, satellite ocean color observations are a flagship of international and national plans for intensified studies of the global carbon cycle.

There are challenges to satellite ocean color beyond routine global observations of chlorophyll biomass if we are to maximize our contributions to the further understanding of the global ocean carbon cycle. First, we need methods to understand how chlorophyll biomass relates to organic carbon. Application of carbon-to-chlorophyll ratios have so far been unsuccessful because of extreme variability in the ratios and poor quantitative understanding of the processes affecting them. Stramski and others have achieved success in limited regional applications in evaluating carbon directly from SeaWiFS water-leaving radiances. Partitioning of the total chlorophyll biomass into phytoplankton functional groups is an extremely important issue because they cycle carbon differently in the oceans and thus have different consequences for carbon budgets not apparent from the total biomass. For example, diatoms tend to grow faster than others, thus uptaking more carbon, but also sink faster, thus representing a potential loss of carbon from the surface layer, and thus from the atmosphere, to the deep ocean. Some types of cyanobacteria can utilize dissolved nitrogen, providing a source for growth and thus carbon fixation, in regions of the ocean that are thought to be limited by the paucity of nitrate and ammonium sources of nitrogen. Coccolithophores are a whole different problem, in that they produce calcium carbonate exoskeletons, called coccoliths, which can change the pH of the oceans, and have major effects on the difference in partial pressures of CO₂ between the ocean and atmosphere. This process is so important that it has been called the “carbonate pump”, placing it in the company of the widely known solubility and biological pumps. Coccolithophores also sink rapidly and represent a potential loss of organic carbon.

Work is progressing on some of these issues. Balch and others are actively developing algorithms to detect coccoliths and calcite production for MODIS. Dupouy, Subramanian, and others have had limited success identifying blooms of *Trichodesmium* spp., a nitrogen-fixing cyanobacterium, using SeaWiFS data.

Identification and quantification of CDOM is also extremely important to the ocean carbon cycle, above and beyond its importance in refining estimates of chlorophyll. It is a component of the total dissolved organic carbon pool in the oceans, which recent estimates suggest is about equal in size to the entire atmospheric carbon pool. Recent progress has been made by Siegel, Hoge, and others in determining the abundance of CDOM, but relationships between its abundance and the dissolved organic carbon pool remain elusive.

Satellite ocean color stands poised to contribute to the understanding of global carbon cycle processes, but many challenges confront us. We have learned much from the CZCS demonstration and our 4-½ year time series from OCTS/POLDER, SeaWiFS, and MODIS. Near future prospects for continued satellite ocean color data are bright. However, the challenges posed by the

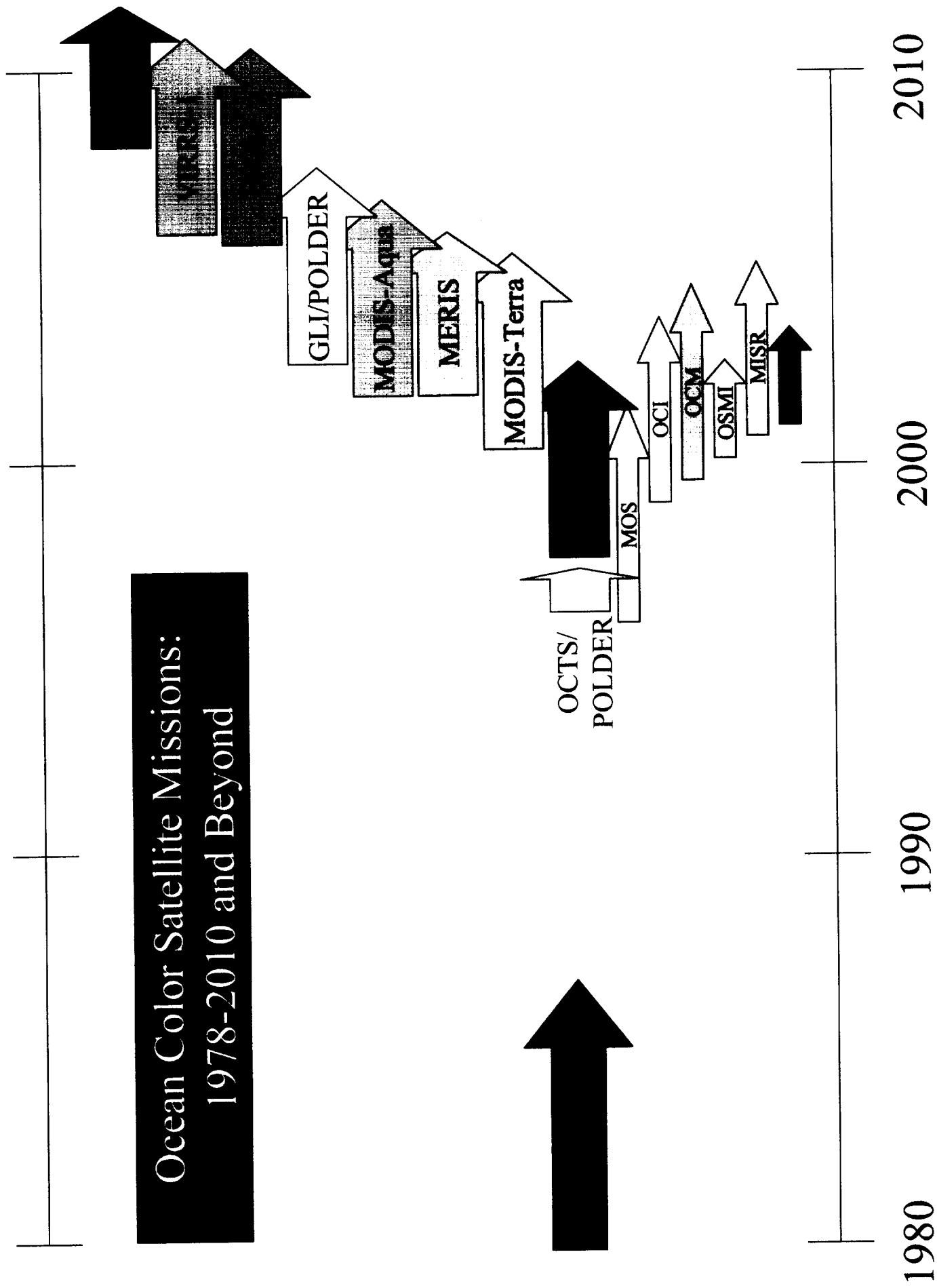
importance of the global carbon cycle require that we work harder to extract the maximum information possible from these satellite data sets. It is our hope and expectation that one day we will look back on our short time series as the beginning of our understanding of the role of ocean color in global climate change.

Figure. CZCS monthly coverage was sparse, due to operational limits for data collection. The modern generation of global ocean color missions, beginning with OCTS, produces nearly complete ocean coverage in typical monthly mean data. Chlorophyll (pigment) concentrations are indicated in the color bar to the right of the figures, in units of mg m^{-3} .

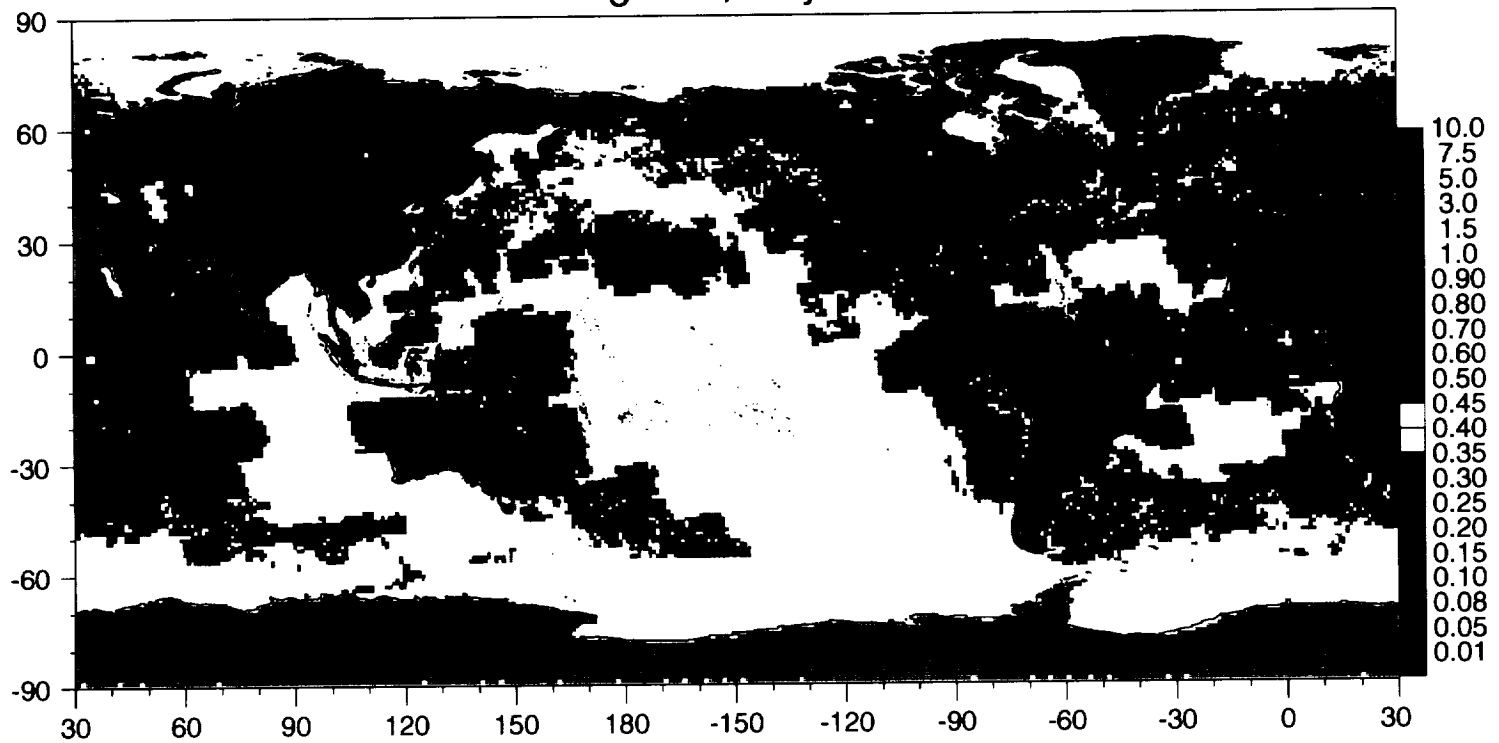
Figure. The dramatic changes in tropical Pacific chlorophyll concentrations due to El Niño and La Niña were captured by SeaWiFS. Nov. 1997 was about the mid-point of the most recent El Niño, and indicated a major decline in chlorophyll in the eastern tropical Pacific. This El Niño had major implications for the global carbon cycle. A La Niña condition followed El Niño in May 1998 and lasted until Sep. 2000. The SeaWiFS Nov. 1999 monthly mean indicates greatly enhanced chlorophyll concentrations that resulted from enhanced easterly winds and vigorous upwelling. By Nov. 2000 more normal conditions prevailed (El Viejo).

Figure. Timeline of the launches of ocean color missions from the past to the future. The thick arrows indicate the global observational missions, and the thin arrows those with a more limited duty cycle/coverage. Mission end times are estimates. The CZCS (Coastal Zone Color Scanner; 1978-1986) was flown on Nimbus-7 by the US National Aeronautics and Space Administration (NASA). MOS (Modular Optoelectric Scanner; 1996-present) flies on IRS-3 by the Indian Space Agency. The OCTS/POLDER (Ocean Color and Temperature Scanner/Polarization and Directionality of the Earth's Reflectances; 1996-1997), was flown on ADEOS-I by Japan's National Space Development Agency (NASDA). SeaWiFS (Sea-viewing Wide Field-of-view Sensor; 1997-present) flies on Orbview-2 by the US OrbImage Corporation. MODIS-Terra (Moderate Resolution Imaging Spectrometer; 2000-present) flies on EOS-Terra by NASA. OCI (Ocean Color Imager; 1999-present) flies on ROCSAT by the Republic of China. OCM (Ocean Color Monitor; 1999-present) flies on IRS-4 by the Indian Space Agency. OSMI (Ocean Scanning Multispectral Imager; 1999-present) flies on KOMPSAT by the Korean Space Agency. MISR (Multi-angle Imaging Spectro-Radiometer; 2000-present) flies on EOS-Terra by NASA. MERIS (Medium Resolution Imaging Spectrometer) is planned to launch in 2001 on Envisat by the European Space Agency. MODIS Aqua is planned to launch in 2001 on EOS-Aqua by NASA. OCTS (Ocean Color and Temperature Scanner) is planned for launch in 2001 on HaiYang-1 by the Chinese National Space Agency. GLI/POLDER (Global Imager/Polarization and Directionality of the Earth's Reflectances) is planned to launch in 2002 on ADEOS-II by NASDA. S-GLI (Super Global Imager) is planned for launch in 2006 by NASDA. VIIRS (Visible and Infrared Sounder) is planned for launch in 2006 on NPP by NASA. Another VIIRS is planned for launch in 2008 on NPOESS by a joint venture including NASA, the National Oceanic and Atmospheric Administration, and the US Department of Defense.

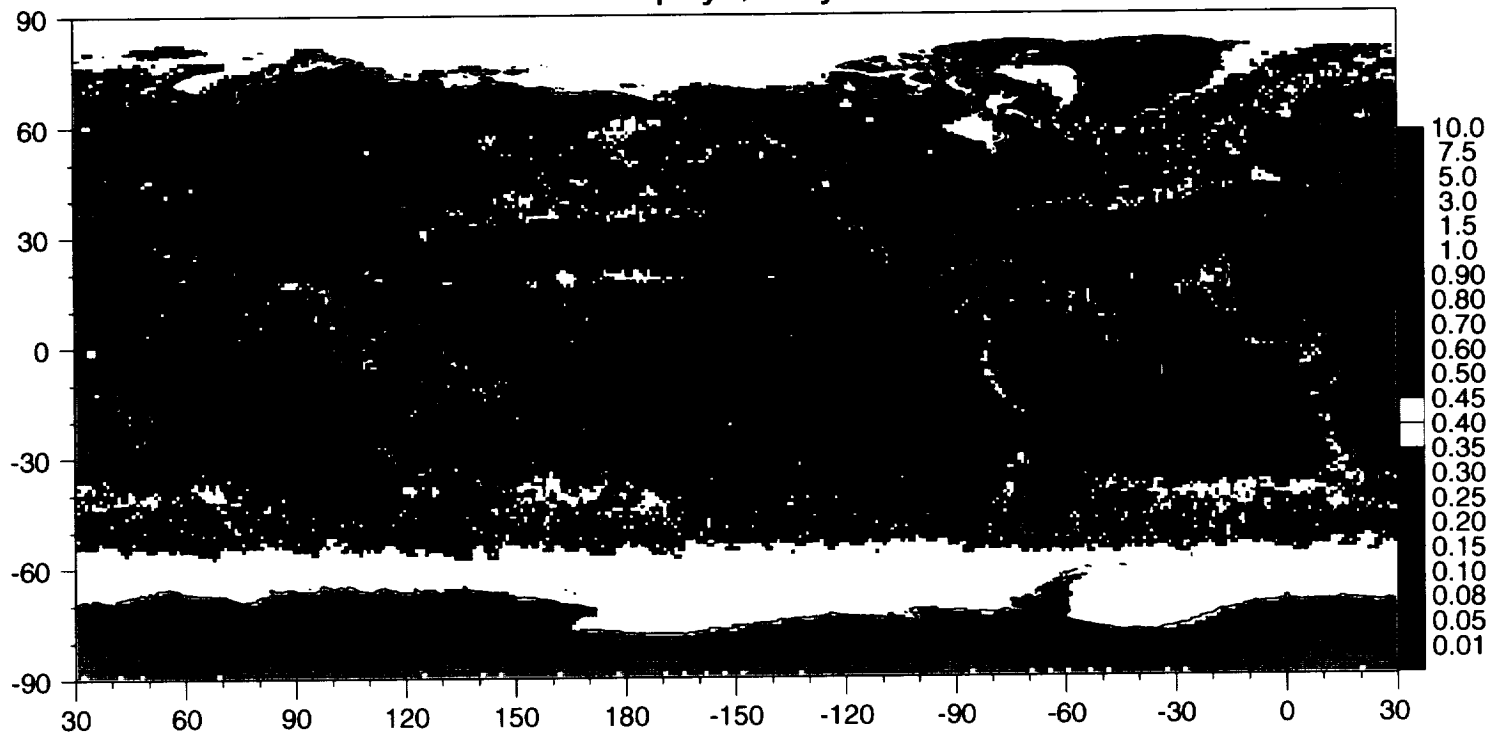
Ocean Color Satellite Missions:
1978-2010 and Beyond



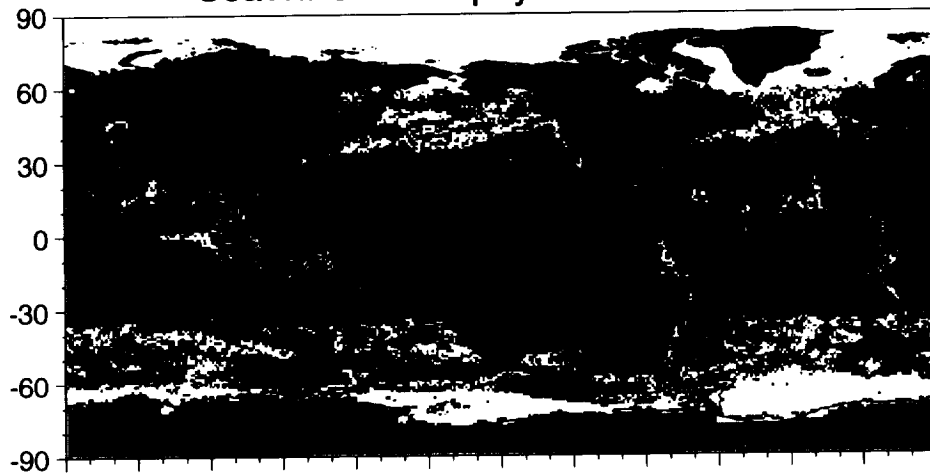
CZCS Pigment; May 1979



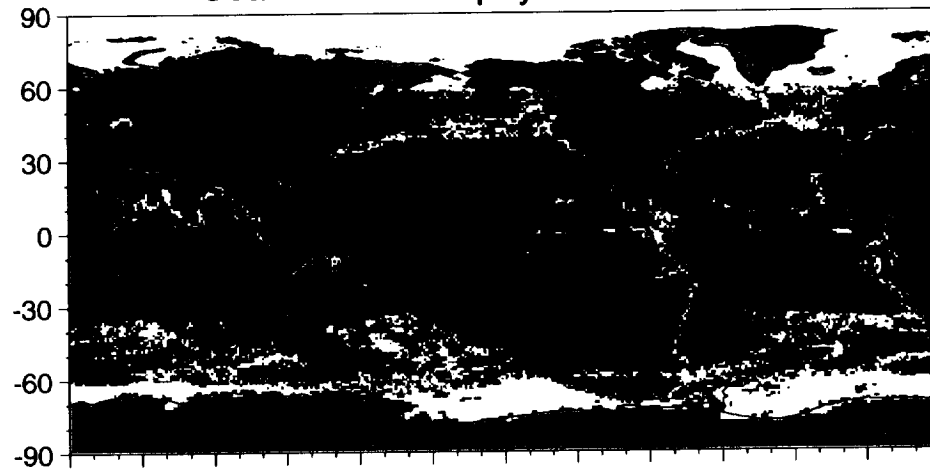
OCTS Chlorophyll; May 1997



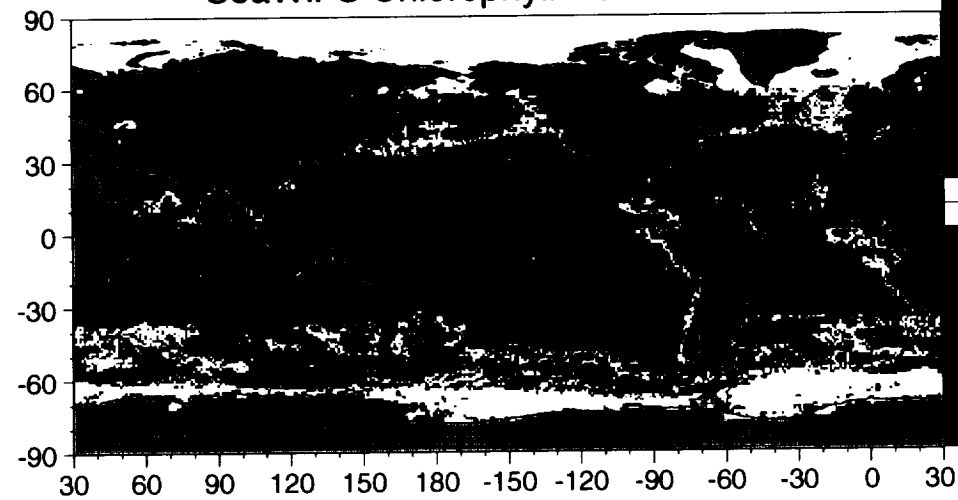
SeaWiFS Chlorophyll Nov 1997



SeaWiFS Chlorophyll Nov 1999



SeaWiFS Chlorophyll Nov 2000



10.0
7.5
5.0
3.0
1.5
1.0
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0.70
0.60
0.50
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0.40
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0.30
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0.20
0.15
0.10
0.08
0.05
0.01

Ocean Color Satellite Missions:
1978-2010 and Beyond

